

WAVELENGTH SELECTION CRITERIA FOR LASER COMMUNICATIONS

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ABSTRACT

Laser communication systems can be based on a wide range of wavelength in the optical and infrared regimes. This article provides a rationale for the selection of wavelengths particularly suited for free space laser communication system. The choice of wavelengths is based on an analysis of propagation issues, especially through the atmosphere, optical background noise, and the necessary technologies that include lasers, detectors, and spectral filters. The maturity of technology is assessed and given due consideration to identify suitable wavelengths for today's laser communication systems. Figures of merit are also developed where useful to provide a comparative estimate of expected system performance as a function of wavelength.

I. INTRODUCTION

The present article is concerned with the development of system level know-how to identify useful ranges and specific wavelengths in the optical regime for communication systems, especially when one of the terminals is well within the atmosphere. Earlier work on the subject is built upon to incorporate the impact of rapid advances in laser and detector technology and improved understanding of atmospheric effects on propagation [1-5]. For the purposes of this work optical wavelengths are restricted to a range between 0.4 to 12.5 μm .

Selection of wavelengths for optical communications depends on an understanding of the propagation channel, both through free space and atmosphere, and on the availability of components and subsystems including lasers, detectors, and optics. Additionally, issues pertaining to availability and reliability of components, especially lasers and detectors for user spacecraft, are critical to the selection of a viable communications wavelength. Considerations of missions and operational issues can also profoundly affect the choice of wavelength, but a detailed study of the consequences of mission design is beyond the scope of this article.

Use of the short wavelengths provides high antenna gain for exoatmospheric (e.g. intersatellite) links. For example, a 0.5 Gb/s LEO to GEO link is possible using 850 nm laser diode and a Si APD detector with a 0.1 m aperture transmitter and receiver and earth in the background [6]. Deep space laser transmitters require high peak power which can be furnished by diode-pumped frequency-doubled Nd:YAG laser as the source. With reasonable assumptions on technology improvement, it has been shown that high rate telemetry (-1.8 Mb/s) is possible from a 0.6

m spacecraft transmitter at Pluto to a 10 m receiver in earth orbit [7].

Like exoatmospheric optical communications, diode lasers, are ideal for range limited earth orbit-to-ground links. For deep space, however, operation at 532 nm results in the highest possible telemetry rates. Calculations show that nighttime telemetry rates of about 1.7 Mb/s are possible at this wavelength for a strenuous Pluto mission [8]. From the mission point of view, if the optical navigation technology matures for longer wavelengths, there may be an advantage in using 1064 or 2000 nm wavelength [9]. However, this choice will decrease telemetry capabilities significantly.

Since non-space qualified redundant higher power lasers and other components can be used and the required command data rates for deep space are low, the uplink transmitter can be designed with greater flexibility and the set of possible operating wavelengths is relatively large. For ground-to-earth-orbit uplinks, especially in a commercial or civilian communications setting, very high data rate (~1Gb/s) links can be envisioned. In this range-limited situation diode lasers at 850 nm can provide high telemetry rates with enough power to cover the required fade margin due to scintillation at this wavelength.

II. FREE SPACE PROPAGATION

Free space propagation loss decreases with wavelength, and provides the single most compelling reason to choose shorter wavelengths for laser communications. The angular beam diameter for a diffraction limited beam as measured by the first Airy disk of the diffraction pattern for a circular aperture is given by $2.44[\lambda/D]$, where D is the diameter of the transmitting aperture and λ is the wave-

length.

Energy density at the receiver is inversely proportional to the square of the beam diameter. For a given distance z and transmitting aperture, the received energy density increases as $1/\lambda^2$. Fig. 1 shows that the energy density decreased by three orders of magnitude as the wavelength increases from 0.4 to 12.5 μm . This provides a strong argument to choose shorter wavelengths for laser communications.

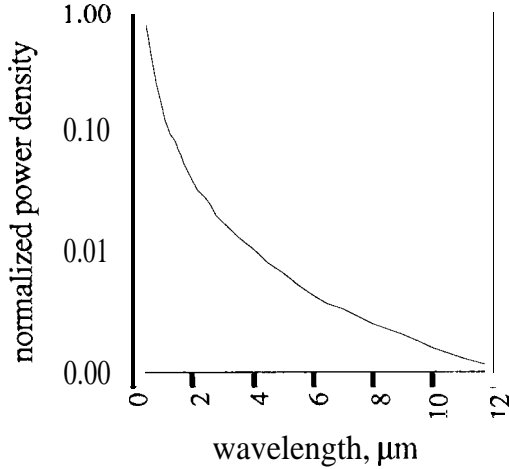


Fig. 1 Normalized far field power density as a function of wavelength

For laser beams with Gaussian amplitude profile, more suitable for the discussion at hand, the beam radius, ρ_L , due to diffractive spreading in free space can be written as [10]

$$(1) \rho_L^2 = (\lambda z / \pi d)^2 + (d/2)^2 (1 - z/R)^2$$

where d is the initial Gaussian beam diameter measured at the 1/e points, $-R$ is the beam radius of curvature, and z is the distance from the transmitter where ρ_L is measured. Later in this article, ρ_L is redefined as the long-term average radius of the beam and eq. (1) is extended to include the effect of refractive turbulence. Note that for collimated beams $R \rightarrow \infty$, and thus the second term in eq.(1) reduces to a constant.

11.1. ATMOSPHERIC PROPAGATION

The atmosphere is a complex and dynamic system [11-13]. Insight on its impact on propagation is necessary to develop reliable optical communication links that must operate wholly or partially within the atmosphere [14-29].

Other than opaque clouds which can occult the communication signal completely, most effects on laser beams arising from atmospheric turbidity and refractive or clear

air turbulence show a marked dependence on the wavelength. Atmospheric turbidity mainly limits signal transmittance as the laser beam is scattered and absorbed by molecules and other particulate constituents [14-15, 30]. Refractive or clear air turbulence degrades the beam quality by distorting the phase front and by randomly modulating the signal power. Wavelength dependence of scintillation on downlink and of scintillation, beam wander, and isoplanatic angle size on uplink are described in this section.

A. Atmospheric TURBIDITY

1. Opaque Clouds

Through cumulus clouds, attenuation of direct signals by more than 100 dB has been observed [31]. Calculated extinction of over 1000 dB for dense fog or clouds in the atmosphere are possible. Since no realistic communication link can exist under opaque cloud cover for optical wavelengths of interest, this subject is not pursued any further. Suffice it to say, the only viable strategy for optical system designers is to avoid such severe atmospheric conditions by employing spatial and temporal diversity [32-33].

2. Absorption and Scattering.

The effect of the atmospheric scattering and absorption is modeled by Bouguer's law, which is stated below.

$$(2) I = I_0 \exp\left\{-\int_0^z \gamma_t(z) dz\right\}$$

where $\gamma_t(z)$ is the sum of all absorption and scattering coefficients due to atmospheric constituents including gas molecules, aerosols, and other particulate matter at position z . The exponent in eq.(2) is defined as the optical depth or thickness, τ , of the atmosphere. Experiments [18] show that the law holds well for optical thickness $\tau \leq 12 \approx -50$ dB. A comprehensive list of references on the subject can be found in [14-17, 34].

Fortunately, LOWTRAN7 (Low Resolution Transmittance, Version 7) developed by Air Force Geophysics Laboratory (AFGL), and now available commercially [35], incorporates all the necessary information to produce spectral transmittance estimates. LOWTRAN7 can be used to estimate transmission and radiance through the atmosphere to characterize an optical communication channel [33, 36]. A typical LOWTRAN7 spectral transmittance curve under nominal weather conditions for wavelengths between 0.4 to 12.5 is shown in Fig. 2. Nominal weather as used in LOWTRAN7 assumes US standard atmosphere 1976 with high cirrus clouds and 17 km (nominal) visibility. Fig. 2 further assumes a 2.3 km receiver site altitude and a zenith path to space. Fig. 2 shows that the transmittance increases from about 0.5 at 0.5 μm to about 0.8 at 2 μm and beyond under nominal weather conditions.

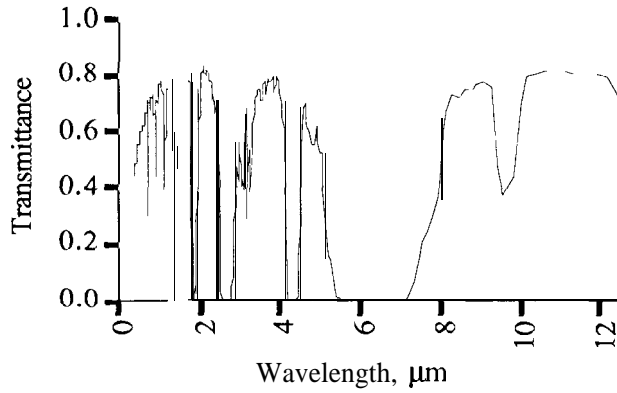


Fig. 2. Atmosphere Transmittance for wavelengths between 0.4 to 12.5 μm. The results are calculated using LOWTRAN7 for near zenith path to space under nominal weather (17 km visibility) for Table Mountain Facility (TMF) at an altitude of 2.3 km.

B. REFRACTIVE TURBULENCE

The relevant effects studied are scintillation, beam wander, and isoplanatic angle. For the downlink, the impact of scintillation on shorter wavelengths can be reduced substantially by the use of aperture averaging for direct detection, the detection method of choice for the ground based receiver. The integrity of the signal wavefront can also be reconstructed by the use of adaptive optics to make heterodyne detection for ground based receiver feasible. The impact of beam wander and the size of the isoplanatic angle is negligible on the downlink and has no significant affect on the choice of wave length.

The impact of beam wander and the size of the isoplanatic angle is relevant to the development of a viable uplink. Additionally, for the uplink the option of aperture averaging to mitigate the effect of fades (and surges) due to scintillation is not available.

1. Atmospheric Model

Modern understanding of atmospheric turbulence is based on the Kolmogorov-Oubokov theory [20]. The characteristics of the fluctuation are described by atmospheric refractive structure constant $C_n^2(z)$, where z is the path or height parameter. Hufnagel [37], Fried [38], and others have developed parametric expressions for the atmospheric structure constant as a function of height above ground. Fried's expression for C_n^2 is given below [38].

$$(3) C_n^2(z) = 4.2 \times 10^{-14} z^{-1/3} \exp\{1-z/z_b\}$$

where $z_b = 3200$ m. Empirical descriptions of the C_n^2 are also available [39]. Typically, for optical wavelengths the

value of C_n^2 ranges from $10^{-17} \text{ m}^{-2/3}$ for weak turbulence to $10^{-12} \text{ m}^{-2/3}$ for strong turbulence near ground.

Results based on a solution of the wave equation using the Markov approximation can be developed when (i) $[2\pi/\lambda]_0 \gg 1$ (forward scattering condition), and (ii) $[2\pi/\lambda]$

$C_n^2 L_0^{5/3} \ll 1$ (little attenuation condition) are satisfied. It can be shown that variance of log-irradiance (fourth moment of amplitude) for a plane wave, for random locally isotropic and homogeneous medium is [20]

$$(4) \sigma_{In}^2 = 1.23 (2\pi/\lambda)^{7/6} C_n^2 \cdot [z \cdot \sec(\alpha)]^{11/6}$$

where α is the zenith angle, Z is the scale height of the atmosphere (8- 10 km), and C_n^2 is the path averaged atmosphere structure constant. An important restriction on the theoretical results is that the log-amplitude or the log-irradiance must remain small. Tatarski derives his results for $\sigma_{In}^2 \ll 4$ and finds good agreement with experiment when $\sigma_{In}^2 \leq 2.5$. Lawrence and Strohbehn note that for vertical and slant paths to space, where C_n^2 varies along the path, there is less chance of exceeding the limit stated above [15].

Another important measure of atmosphere's effect on propagation can be described by its coherence parameter. The atmosphere coherence parameter p for a locally isotropic and homogeneous medium is given by

$$(5) P = [0.56 (2\pi/\lambda)^2 C_n^2 \cdot Z]^{4/5}$$

The impact of the coherence parameter is to broaden the optical beam beyond the diffractive beam spread, The short-term averaged beam radius at the 1/e point, $E\{\rho_s^2\}$, for weak turbulence when $\rho_0 \ll d \ll L_0$ and $z_0 \leq (2\pi/\lambda)d^2$ can be written as

$$(6) E\{\rho_s^2\} = (\lambda z_0/\pi d)^2 + (d/2)^2 (1-z_0/R)^2 + (\lambda z_0/\pi d)^2 [1 - 0.62(\rho_0/d)^{-1/3}]^{6/5}$$

Note that $p_L = p_s$ in free space as $p \rightarrow \infty$, and eq.(6) reduces to eq.(1). Computations show that the results obtained from eq.(1) and eq.(6) for most paths through the entire atmosphere do not differ by more than a few percent [39].

2. Scintillation

Refractive turbulence causes fluctuations in irradiance of a light wave by redistributing its power spatially in time. The observed turbulence induced fluctuations or scintillation is not very different from the speckle patterns that are observed when laser beams are scattered from phase screens. The strength of scintillation can be measured in terms of the variance of the beam amplitude or irradiance (see eq.(4) above). Note that the strength of irradiance fluctuations decreases as $\lambda^{-7/6}$. Fig. 3 shows a plot of this wavelength dependence over the range of interest. The variance of log-irradiance or the strength of scintillation drops about two orders of magnitude as wavelength increases from 0.4 μm to 12.5 μm .

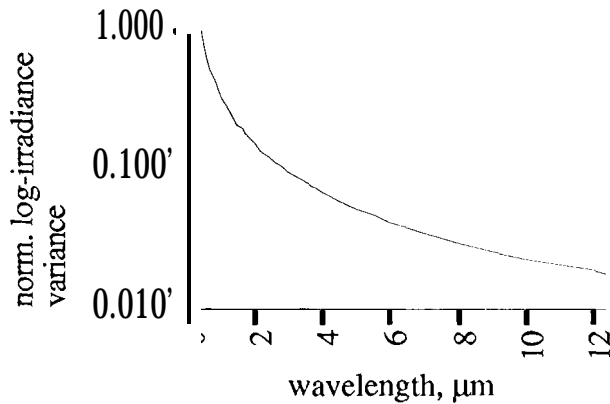


Fig. 3 Normalized log-irradiance variance as a function of wavelength

Scintillation produces both temporal and spatial irradiance fluctuations at the receiving aperture which results in power surges and fades [40]. For operation at 2000 nm when log-irradiance variance is about 0.15, 4 dB fades occur about 1 percent of the time with a frequency and duration of about 150 Hz, and 10 μs , respectively.

Table I shows fade statistics for selected wavelengths. Log-irradiance variance for each of the wavelengths is calculated assuming 30 m/s wind and a 45° zenith angle for propagation using Hufnagel approximation [40]. It shows that for 532, 1064, and 2000 nm wavelengths 4 dB fades are calculated to occur 26, 10, and 1 percent of the time, respectively. From Table I, when 850 nm diodes are used for near-earth uplink, a 7.1 dB fade margin must be provided for 99 percent operation. Calculations show that in general such fade margins can be provided for near-earth uplink communications at 850 nm.

The scintillation statistics discussed above are true for a point receiver. If the receiver has a finite aperture much larger than the atmospheric coherence diameter at the receiver, the observed effect of scintillation is spatially averaged over the collecting surface [40-43]. The strength of received irradiance fluctuations is found to decrease with the increasing size of the aperture. This effect, known as

aperture averaging, reduces the probability of fades (and surges), and has been observed experimentally. Yura and Mckinley [43] have found an engineering approximation for the magnitude of this effect on ground based receivers. They show that in the optical regime the irradiance variance is reduced by three orders of magnitude in going from 0.1 m to a 1 m receiving aperture.

Aperture averaging is generally not available at the spacecraft for uplink applications. The speckled energy distribution at the top of the atmosphere is carried through free space to the spacecraft receiver at a very large distance; each of the speckle cells, defined by the coherence parameter, growing in size with distance. Thus the phase coherence radius at the receiving aperture on a spacecraft is much larger than the probable size of the receiver (< 1 m), and no aperture averaging is possible.

The impact of amplitude and phase coherence fluctuations, the underlying basis of scintillation, is large enough to severely limit operation of heterodyne receivers on the ground. Successful operation of heterodyne operation of optical communication links through the atmosphere requires use of adaptive optics techniques to compensate for the wave front distortion.

3. Beam Wander

Beam wander is independent of the wavelength, whereas, the diffraction limited beam size grows with wavelength. In general, at some distance, z , from the transmitter one would observe a beam spot of radius ρ_s which is deflected away from the boresight by a distance ρ_c at any given instant. The time constant for these deflections is of the order of 0.01 s. The beam spot radius ρ_s is somewhat broader than the predicted diffraction-limited spot, due to atmospheric effects. As the gaseous blobs flow across the beam, the laser beam is continuously deflected in different directions and ρ_c changes randomly in time. A long time exposure ($\gg 0.01$ s) will show a wandering beam spot with a mean square radius, $E\{\rho_L^2\}$, given by [10]

$$(7) \quad E\{\rho_L^2\} = E\{\rho_s^2\} + E\{\rho_c^2\}$$

where ρ_L and ρ_s are defined as the radii at which the long- and short-term averaged irradiance distributions are reduced by a factor of e^{-1} from their maximum values. $E\{\rho_c^2\}$ has different solution regimes. For weak turbulence when $\rho_0 \ll d \ll L_0$ and $z_0 \ll (2\pi/\lambda)d^2$, it can be shown that

$$(8) \quad \phi_c^2 = 3.43 (\lambda/2\pi)^2 \rho_0^{-5/3} d^{-1/3} = 192 C_n^2 \cdot z_0 d^{-1/3}$$

Table I. Fade statistics for selected wavelengths

Wavelength μm	Log-irradiance variance [1]	Fraction of time faded ≥ 1 dB	Fraction of time faded ≥ 4 dB	Minimum fade margin for 99 percent operation, dB
0.532	0.73	0.26		9.7
0.85	0.42	0.13		7.1
1.064	0.34	0.1		6.3
1.3	0.25	0.06		5.3
2.0	0.15	0.01		4.0
2.91	0.1	0		3.3
10.6	0.02	0		1.3

[1] Log-irradiance variance is calculated for 30 m/s wind and a slant path through space at 45° zenith angle

where $\phi_c = [E\{\rho_c^2\}/z_0]^{1/2}$ is angular beam wander radius. Eq.(8) agrees well with measured data provided $(2\pi/\lambda)^2 C_n^2 z. d^{5/3} < 1600$, a condition signifying weak turbulence [17].

For stronger turbulence, when $(2\pi/\lambda)^2 C_n^2 z. d^{5/3} > 1600$, $E\{\rho_c^2\}$ saturates. Increasing path length or turbulence strength no longer increases beam centroid displacement. While the beam wander does not increase significantly, the beam begins to break up in multiple beams. In this case a short exposure picture will consist of many spots at random locations on the receiving aperture [17]. Under most realizable conditions, the angular beam wander radius ϕ_c saturates at about 9 μrad .

As stated before, the beam wander is independent of the wavelength (In eq.(8) the product $\lambda^{2/3} \rho_0$ is independent of wavelength). The fraction $E\{\rho_c^2\}/E\{\rho_s^2\}$, decreases with increasing wavelength, i.e., the diffraction limited beam size grows with wavelength when the estimated beam wander remains unchanged, Beam wander as a fraction of the beamwidth decreases as λ^2 , thus reducing difficulty of beam pointing for longer wavelengths,

4. Isoplanatic angle

The uplink transmitter must point ahead of the received beacon by several tens of μrad to compensate for the relative motion of the spacecraft in deep space. Fried defines isoplanatic angle, ϕ_1 , as the maximum angle away from a certain optical path for which the turbulent behavior of the atmosphere can be considered the same. For weak turbulence, the isoplanatic angle is given by [44]

$$(9) \phi_1 = [2.91 (2\pi/\lambda)^2 \{\sec(\alpha)\}^{8/3} \int_0^z C_n^2(z) z^{5/3} dz]^{1/3} \quad (3.5)$$

A typical value for ϕ_1 at $\lambda=500\text{ nm}$ is 10 μrad for a near-zenith path to space [39]. The size of the isoplanatic angle increases with wavelength as $\lambda^{6/5}$. Fig. 4 shows that under similar turbulence conditions longer wavelengths will allow larger point-ahead angles for uplink in the presence of turbulent distortions.

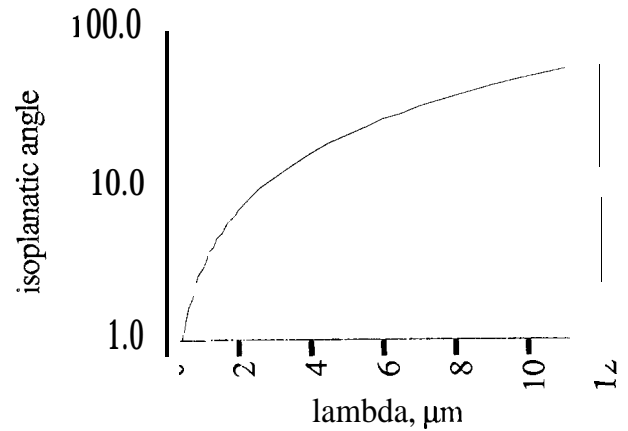


Fig. 4 Normalized isoplanatic angle as a function of wavelength

IV. OPTICAL BACKGROUND

Optical communications system performance in terms of data rate varies significantly between night and day. Over most of the celestial sphere, the radiance of the zodiacal light is of the order of 10^3 to $10^{-1} \text{ nW}/(\text{m}^2 \cdot \text{sr} \cdot \text{nm})$ concentrated primarily in the wavelength region of 7 to 30 μm [39, 4S-46]. At such low light levels the wavelength dependence of background has no significant impact on the optical communication link design for planetary or near-earth missions.

Direct sun is a powerful source of optical radiation. The spectral irradiance of the sun peaks at 460 nm as expected from black body considerations, and decreases with increasing wavelength [39]. Direct sun can be avoided by

accepting some loss in coverage. The ground receiver station can be designed and operated such that the sun is never allowed within the field of view of the communications system.

Spectral sky radiance on ground depends on solar elongation (sun-earth-spacecraft angle) as shown in Fig. 5 for short wavelengths. For wavelengths larger than $4\text{ }\mu\text{m}$ the atmosphere acts as a secondary source of radiation and the total sky radiance does not change with solar elongation. The sky radiance for shorter wavelengths decreases by an order of magnitude as the solar elongation increases from 10° to 150° , while for wavelengths longer than $4\text{ }\mu\text{m}$ remains unchanged. Fig. 5 was generated by LOWTRAN7 under nominal weather (17 km visibility) for Table Mountain Facility in California at an altitude of 2.3 km.

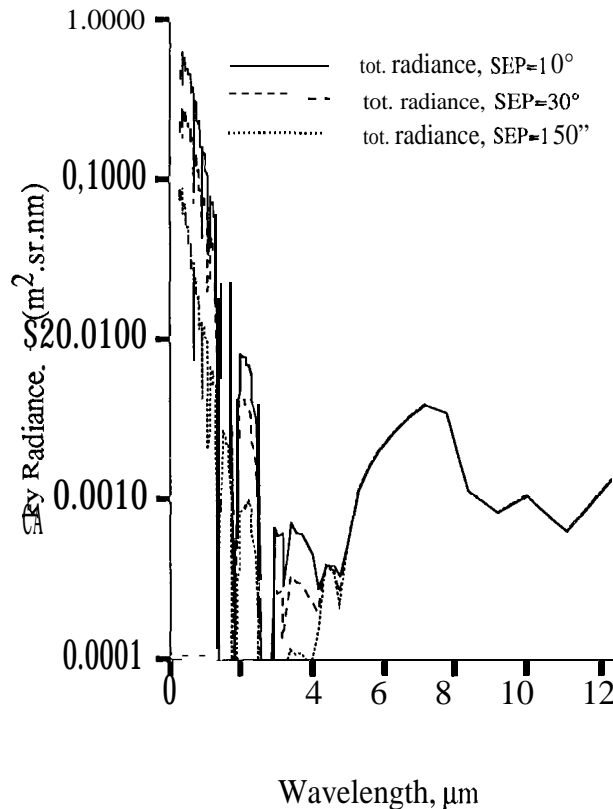


Fig. 5 Sky radiance as a function of wavelength for selected solar elongation at an altitude of 2.3 km. Other parameters are: US Standard Atmosphere with cirrus clouds, nominal 17 km visibility, 60° sun zenith angle, and 60° line of sight zenith angle through the atmosphere.

Fig. 5 shows that the sky background radiance drops by three orders of magnitude as wavelength increases over the range of interest. However, note that the received signal energy density also drops by three orders of magnitude over the same range of wavelengths (see Fig. 1).

There is a potential source of background optical radiation entering the field of view (FOV) of the communication system as the sunlight (or any other source of light) is scattered at the receiving instrument, i.e., the primary mirror and other telescope fixtures. However, it can be shown that the light scattered at the instrument is much weaker than the sky background radiance, which enters the receiver FOV co-linear with the signal, and can be neglected.

Moonlight is another source of background radiation, however, its impact on the communications link is much smaller than that of the sun. Spectral irradiance of full moon is about $4.8\text{ }\mu\text{W/m}^2/\text{rim}$ at sea level for one atmosphere [39]. Like the sun the operation of the optical communication system can be designed to exclude the moon from the FOV of the instrument to further decrease the impact of moonlight.

It is highly desirable to develop optical communication systems around Fraunhofer lines where the sun's spectral irradiance is substantially low. However, assuming present technology, it is difficult to see how this information can be used to advantage. It is a technical challenge to produce an optimal match between the laser wavelength and a strong Fraunhofer line, and, in addition, most practical lasers for optical transmitters have broader line widths than the fine atomic dark lines in sun's spectrum.

V. PROPAGATION IMPACT SUMMARY ON WAVELENGTH SELECTION

Fig. 1 shows that in free space the energy density decreases by three orders of magnitude as the wavelength increases from 0.4 to $12.5\text{ }\mu\text{m}$. This provides a strong argument to choose shorter wavelengths for laser communications.

For ground based reception of optical communications, the deleterious effects of atmospheric turbidity and turbulence provide some reasons to consider longer wavelengths. How the impact of the atmosphere is brought to bear on the choice of wavelength for optical communications is summarized below.

First, the atmospheric turbidity reduces signal transmittance. The transmittance loss through the atmosphere is wavelength dependent and under nominal weather conditions varies from about 3 dB at $0.5\text{ }\mu\text{m}$ to about 1.0 dB at $2\text{ }\mu\text{m}$ and larger wavelengths within the range of interest, excluding the bands where the atmosphere absorbs radiation strongly. The transmittance loss as shown in Fig. 2 does not decrease significantly for wavelengths beyond $2\text{ }\mu\text{m}$ whereas the energy density continues to drop due to diffraction as the square of the wavelength. Therefore from the standpoint of atmospheric transmittance there is no advantage in choosing a wavelength much larger than $2\text{ }\mu\text{m}$ for optical communications.

Second, refractive turbulence degrades the beam quality by distorting the phase front and by randomly modulating the signal power. For downlink using non-coherent detection methods where high beam quality is not

needed, the impact of atmospheric turbulence on ground receiver system design is minimal. The size of the blur diameter contemplated for ground based photon-bucket receiver system is about 0.1 mrad whereas the size of blur diameter contribution expected from the atmosphere is not likely to be much larger than 0.02 mrad. If coherent ground based reception is desired, adaptive optics is necessary to reconstruct the signal wavefront. Whereas longer wavelengths are favored for ground based coherent reception due to less severe turbulence effects, adaptive optics technology for the visible and near infrared wavelengths available today is perhaps adequate though expensive for coherent optical downlink applications.

Since the atmosphere is in front of the ground based transmitter, the impact of refractive turbulence is significant on the optical uplink. Scintillation, beam wander, and isoplanatic angle considerations favor longer wavelengths. However, note that the uplink data rates traditionally provided by the Deep Space Network as well as an optical beacon, if needed, require very low bandwidth (≤ 1 Kb/s). Additionally, since the transmitter is ground based, non-space qualified redundant higher power lasers and other components can be used, allowing much greater flexibility in the design of the transmitter. For example, (i) deeper fades due to scintillation at shorter wavelengths can be countered by redundant uplinking of data, and the beacon can be acquired by the user spacecraft by integrating over times much longer than the coherence time of the atmosphere (~ 1 msec), (ii) design of broader transmitter beams using high power lasers at short wavelengths and use of adaptive optics for predicting and compensating for beam direction can mitigate the impact of beam wander, and (iii) a point ahead of about 50 μ rad can be handled within the isoplanatic patch when a wavelength near 2 μ m is used. If much larger point ahead become necessary, use of other strategies including redundant uplinking of command data will be necessary. Alternatively, some power loss due to scintillation fades can be designed into the uplink budget.

Third, the impact of background noise on the signal detection process, as discussed above, is to favor shorter and midrange wavelengths to achieve higher signal to noise ratio, as the atmosphere begins to act as a strong source of background beyond 4 μ m wavelength.

Table II shows how the propagation through free space and the atmosphere affects choice of signal wavelength by quantifying its impact on selected wavelengths over the spectral range of interest. Column 2 in Table 11 lists normalized energy density at the receiver for selected wavelengths. The subscript 's' refers to the value of a quantity at the normalizing wavelength, i.e. 0.4 μ m. Column 3 shows atmospheric transmittance through the atmosphere for selected wavelengths. Column 4 provides estimate of normalized scintillation, beam wander to beam width ratio where $\rho_{1/2}$ is the angular Gaussian beamwidth when $z \gg 1$ and $d = 0.5$ m, and normalized isoplanatic angle for weak turbulence.

Column 5 summarizes the impact of propagation for a ground based receiver. The expression used to calculate

the normalized propagation figure of merit (FOM) is $(\eta_a/\eta_{a,s})(\lambda/\lambda_s)^{-2}/(x\lambda/\lambda_s\lambda_s)$. η_a and x are atmospheric transmittance and background sky radiance for night or day as calculated by LOWTRAN7. The normalized propagation FOM is the product of relative transmittance, the relative signal power, and the reciprocal of relative noise fluctuation. It is assumed that all common system parameters including laser power, transmitter efficiency, receiver optics efficiency, detector quantum efficiency, etc. are the same for all wavelengths.

The nighttime propagation FOM, as expected, strongly favors short wavelengths. Additionally, note that propagation FOM for high daytime background has the same order of magnitude for wavelengths between 0.4 to 4 μ m. As the atmosphere begins to act as a source of background noise beyond 3 μ m and the background radiance does not decrease (see fig. 5), the propagation FOM falls by an order of magnitude. The operation of optical communication system, even in daytime under high daytime sky background radiance, favors shorter to mid range wavelengths to achieve good propagation FOM. Note that during the nighttime and under average daytime background, when the background at shorter wavelengths is smaller, the propagation FOM is several orders of magnitude higher for shorter wavelengths.

Table 11 confirms that overall propagation effects favor shorter wavelengths providing higher gain at the receiver and good propagation FOM even for high daytime background. The effects of the atmosphere including scintillation, beam wander, and isoplanatic angle are not significant enough to shift the balance toward longer wavelengths for the downlink. These effects are critical to the design of the uplink. Their impact on the uplink, however, can be considerably reduced by choosing a wavelength between 1000 to 2000 nm for deep space. For near-earth missions when excess transmit power is available to absorb loss due to fades, and when very high data rates are required, use of laser diodes at 850 nm is indicated.

Note that the foregoing conclusions are based entirely on the propagation characteristics of the signal radiation through free space, atmosphere, and channel noise. Accordingly, considerations of missions, operational issues, and selection of communication system components like lasers and detectors can profoundly affect the choice of wavelength.

VI. DETECTORS

Optical communications with its promise of high data rates has, since the inception of the laser, provided strong incentives for the improvement and the development of detectors including fast photodiodes [48-52], high speed photomultipliers [53-54], and the development of avalanche photodiode [50-52, 55-58]. The applicability of the detectors for optical communications can be measured by several figures of merit which include quantum efficiency, gain, defectivity, bandwidth, and reliability. The final choice of the detector and the operating wavelength, how-

Table II. Comparison of selected wavelength>

Wave-length	Normal-ized en-ergy density at re-ceiver [1] $(\lambda\lambda_s)^{-2}$	Trans-mitt-ance [2]	Atmosphere			Normalized propagation FOM $(\eta_a/\eta_{as})[(\lambda\lambda_s)^{-2}/(x\lambda/x_s\lambda_s)]$	
			Scintillation, nor- realized log irradi- ante variance[3] $\sigma_{ln}^N = (\lambda\lambda_s)^{-7/6}$	beam wander to beamwidth ra- tio[4] $\phi_c/(\rho_L/z)$ with $z \gg 1, d=0.5 \text{ m}$	normalized isoplanatic an- gle [5] $\phi_c^N = (\lambda\lambda_s)^{-6/5}$	Night time ' 1''	High Daytime (SEP angle- 10°)
0.4	1	0.45	1	39.3	1	1	1
0.532	0.57	0.59	0.7	29.5	1.5	0.56	0.44
0.820	0.24	0.69	0.4	19.2	2.4	0.13	0.30
1.064	0.14	0.77	0.32	14.8	3.1	0.06	0.35
1.300	0.1	0.75	0.25	12.1	4.1	0.02	0.36
1.500	0.07	0.66	0.21	10.5	4.9	0.01	0.47
2.000	0.04	0.51	0.15	7.9	6.9	0.001	0.82
3.0	0.02	0.48	0.1	5.2	11.2	1.4×10^{-6}	1.75
5.0	0.01	0.8	0.05	3.1	15	6.3×10^{-9}	0.47
10.6	0.001	0.81	0.02	1.5	50	6.6×10^{-10}	0.05

[1] Energy density at receiver is proportional to λ^{-2} , [2] Nominal weather conditions, see Fig. 2, [3] Aperture averaging can be used to reduce log-irradiance variance by three orders of magnitude for downlink, [4] significant for uplink only. Under nominal weather beam wander is $\leq 10 \mu\text{rad}$ for all wavelengths considered, [5] Significant for uplink only

ever, depends on the system and link requirements.

There are two major types of detectors: thermal and quantum. Thermal detectors operate by detecting changes in temperature as light energy is absorbed over a blackened surface. This change in temperature can be measured in a variety of ways to infer light detection including change of voltage (thermocouple), electrical resistance of a metal or a semiconductor (bolometer), change in polarization of certain materials (pyroelectric), or change in pressure of an enclosed gas (Goley cell) [58]. Thermal detectors are unsuitable for optical communications due to their low bandwidth (~1 KHz), and are not discussed further.

Photon detectors convert incoming photons directly to charge carriers. Three basic types of photodetectors are available. They are (i) Photomultiplier Tube, PMT, (ii) Photodiode, PD, and (iii) the Avalanche Photodiode, APD. The performance of these detectors is discussed below.

A. PHOTOMULTIPLIER TUBE

The PMTs using multi-alkali materials (Na-K-Sb-Cs) for the photocathode show good response from the UV to near IR. When a photon impinges on the photocathode, it generates a primary photoelectron with certain probability (quantum efficiency). The photoelectron is accelerated and made to impinge on a surface (dynode) and generate secondary photoelectrons by the action of a strong electric field. This process continues over several stages. The number and the material of the dynodes determines the gain

or the ratio of the number of output electrons to the number of primary photoelectrons generated at the cathode.

The PMT is the most sensitive detector available in the UV to near IR range of wavelengths, and can be used to detect single photon events [53-54]. The wavelength response can be extended to longer wavelengths (~1 μm) by special processing. The quantum efficiency for the device is about 0.33 near 0.4 μm , and it drops to less than 0.01 at 1.064. The gain is near noise free and is between 105 and 10^7 . The bandwidth of the PMT can be as high as 1GHz. PMTs are very reliable; values of mean time to failure (MTTF) for partial to full failure are of the order of 10^6 hours of operation [59]. The PMTs have flown in space and are rated at highest NASA readiness levels (8 or 9). However, note that the size and weight, and the requirement of maintaining high electric fields to achieve high gain make PMTs less attractive compared to semiconductor devices for use in space. Additionally, due to the extremely sensitive operation, PMT cannot be used in high background optical noise conditions such as during the daytime ground-based reception.

B. PHOTODIODE

Photodiodes (Si, Ge, GaAs, InAs, HgCdTe) cover the full range of wavelengths between 0.4 to 12.5 μm . A PD is a unity gain device, so post detection electronic amplification

Table III. Photodiode (PD) Parameters [48-52]

Detector	usable wavelength range, nm	Defectivity $\text{cm} \cdot \text{W} \cdot \text{Hz}^{1/2} \times 10^{12}$	Quantum Efficiency	Freq. Response (3dB Points), GHz	Gain	NASA Readiness Level	Remarks
Si PIN	350-1130 (850 nm peak)	0.1 @ 1064 nm 100 @ 850 nm	0.5 @ 1064 nm 0.9 @ 850 nm	>1	1	8/9 used in space	No gain. Amplifier noise 'dominated' 77-195K High internal noise (Galileo)
InAs	1000-3800	0.04	0.85	5	1	8	
HgCdTe	1000-5500 (photovoltaic) 8000-14000 (photoconductive)	0.025	0.85	2	-1	5/6	77 K High internal noise

tion of the resulting signal is required.

Table III lists PD parameters for selected PDs. Si PIN diode is preferred in the 0.4 to 1.13 μm range because it is technically more mature. InAs and HgCdTe are less developed but can be used for the longer wavelengths between 1 to 14 μm .

For Si PIN PDs the peak quantum efficiency is 0.9 at 850 nm. Quantum efficiency and other parameters for the Si PIN PD are shown in Table III for selected wavelengths. The PD detectivities (reciprocal of noise equivalent power) are high, and the response bandwidth can be greater than 1 GHz. They are reliable, and have been used in space (NASA readiness level 8 or 9). The PD can operate in high optical background noise; but the detection process is dominated by the amplifier noise. The PD, however, has no gain which limits its usefulness as compared to the APD. Parameters for Ge and GaAs devices are not listed in Table III since PDs using these materials generally operate in the similar range of wavelengths as the Si PDs, are less developed, and do not provide significant advantages.

InAs technology operating between 1 to 3.8 μm is well developed, but it is less suitable for optical communications since it has high internal noise (low defectivity) and requires cooling. HgCdTe PD technology is not mature, has high internal noise, and it has not been tested in space (middle NASA readiness level 5 or 6).

C. AVALANCHE PHOTODIODE

Wavelengths of operation and the quantum efficiencies for the APDs are similar to the PDs. They differ in that the APDs provide an additional region where the photo-generated charge carriers are multiplied (gain) via the avalanche process. The carriers in the gain region are accelerated by an electric field ($\sim 10^5$ V/cm) which culminates in the acquisition of enough kinetic energy to create new carrier pairs on impact ionization.

Si, AlGaAs, InGaAs, and Ge based APDs are listed in Table IV. Si APD technology is mature, and it has been

used in space (NASA readiness level 8 or 9). These devices have peak quantum efficiency about 0.9 at 0.85 μm , high response bandwidth, and modest gain. The gain, however, is not noise free.

When a Si APD is operated in the Geiger mode, the gain can be comparable to a PMT, but the quantum efficiency drops to about 0.22 at 1.06 μm . This technology is at NASA readiness level 4. Further development of these devices is required for space qualification.

Other APDs shown in the Table IV extend the usable wavelength range to about 2 μm . InGaAs APD has high quantum efficiency, 7 GHz response bandwidth, small gain with high internal noise. If system considerations indicate use of longer wavelengths, this technology can possibly be used for wavelengths up to 2 μm albeit with higher reliability risk and higher internal noise.

D. DETECTOR SELECTION IMPACT ON WAVELENGTH CHOICE

The requirements for both the downlink and the uplink detector include an opportune combination of high quantum efficiency, low internal noise, high frequency response, and high gain. Additionally, the uplink detector should be very reliable (NASA readiness level 8 or 9) with long mean life (~ 15 years), and low power consumption, mass, complexity, and thermal management overhead.

From the discussion above it can be inferred that detectors suitable for laser communications limit usable wavelengths to about 1 μm and less. This range is extendible to 2 μm if some risk in reliability and higher detector noise is acceptable. HgCdTe detectors can be used on ground when cooled to 77 K to extend the usable wavelengths to 12.5 μm , but are not a reliable option for uplink at the present state of development.

1. Detector for ground reception

Primary candidates for the downlink are PMT and Si APD. The use of PMT being limited to the nighttime op-

Table IV. Avalanche Photodiode (APD) Parameters [50-52, 58]							
Detector	usable wavelength range, nm	Detectivity (D*) cm-WHz ^{1/2} x 10 ¹²	Quantum Efficiency	Frequency Response (3 dB Points), GHz	Gain	NASA Readiness Level	Remarks
Si APD	0.4-1.1 (850 nm peak)	0.1 @ 1064 nm	0.4 @ 1064 nm	2	300	8/9	Gain is not noise-free
Geiger-Mode Si APD		50 @ 532 nm	0.8 @ 532 nm	0.001 (passive.) 0.01 (active)	10 ⁴ -10 ⁶	4	Gain is not noise-free
AlGaAs Staircase APD		100 @ 850 nm	0.9 @ 850 nm	> 0.5	--300	-3	Developmental
InGaAs APL	800-2200 :1600 peak	0.4 @ 1600 nm	0.13 @ 830 nm 0.74 @ 1064 nm run	3	up to 50	6/7	High internal noise
Ge APD	800-1800		0.78 @ 1064 nm run	>1	200	5/6	High internal noise

eration only. The operation of these detectors is limited to visible and near IR range of wavelengths. The InGaAs APD is useful for wavelengths up to 2 μm . It has high quantum efficiency (~0.74 at 1064 nm) and modest gain (50), but comes with high internal noise and is less developed. Useful Developmental detectors include Staircase and Geiger mode APDs.

2. Detector for Spacecraft

Viable Candidate detectors for the uplink include the Si PINPD, and Si APD which has better noise performance. The PMT, which operates in a range of wavelengths similar to the Si PD and the APD, is not recommended due to its bulk, and its requirement for high electric fields and low background noise for operation.

Si PD and the APD detectors operate at wavelengths about 1 μm and less. InGaAs detectors can be used to extend the usable wavelength range to 2 μm . InGaAs APD provides higher quantum efficiency relative to Si detectors at longer wavelengths, but with higher internal noise and risk in reliability. If internal noise of the InGaAs detectors decreases, or if sufficient signal is available to overcome the higher internal noise, this detector can be a viable candidate.

VII. LASERS

Since the inception of the laser, attempts to develop a practical optical communication system has continued unabated [60]. A representative list of lasers covering the range of wavelengths under consideration (0.4 to 12.5 μm), and their properties relevant to optical communications is shown in Table V. Data shown in this table on selected commercially available lasers is taken from ref. [61-64].

A. LASER REQUIREMENTS AND TECHNOLOGY

Lasers suitable for non-coherent optical communications through the atmosphere must operate reliably and provide high peak and average power (range dependent), good beam quality, and modulability. The requirements for high data rate downlink (laser in space) are very stringent compared to the uplink (laser on ground). Additional requirements on the downlink laser include high pulse repetition frequency (PRF), short pulsewidth, high wall plug efficiency, high amplitude stability, high modulation extinction ratio, single spatial mode output beam, low weight and power consumption, compact size, long life (~15 years), and minimal need for thermal management. For coherent detection additional frequency dependent properties are required. It is shown that the appropriate lasers for optical communications, especially for the terminal in space, restrict the range of useful wavelengths to the visible and the near IR range. The range of useful wavelengths can be extended to 10.6 μm or longer for the ground transmitter as the requirements on reliability, mass, power consumption, etc. can be relaxed.

Earlier laser communication systems used gas lasers to demonstrate optical data links in the laboratory [65]. Properties of Argon, Krypton, iodine and copper vapor, carbon monoxide and carbon dioxide are shown in Table V. None of these lasers have been tested in the space environment. Gas lasers are bulky and fragile, and their operational life time is limited to about one year as the active gas medium is lost due to leakage. Properties like the short life time, high mass and high power requirements (low modulated power efficiency), and usually long pulsewidths eliminate gas lasers from being a reasonable choice for space use (see Table V). Possible applications of gas

Table V. Properties of Lasers in the 400 To 12000 nm Wavelength Range [61-64]

LASER	Wave-length nm	Modulated Efficiency, percent	Maximum Power, W Av/cw	Maximum Energy per Pulse, J	Pulse- width Hz	Weight kg	Lifetime snots(sn) or hour(h)	NASA Readiness Level
Ion (Ar, Kr, ...)	450-800	<< 1	20	-	-	> 100	1 (h)	6
Copper Vapor	510	< 1	100	8 k	0.02	19 ms	< 100 (< 100 (sh)	6
Excimer Vapor (atomic)	1315	< 2	3	10	5 ms	> 50	< 1 (h)	6
HF, DF	2600-4000	< 2	500	0.03	25	0.15 ms	> 50 (< 0.1 (h)	6
CO	5000-6500	< 2	10	-	-	> 50	> 1 (h)	6
CO ₂ (Sealed-tube, Pulsed TEA, Waveg.)	9000-11000	5-20	1 k	5 k	50 kHz	0.01 ms	20-1000 10 (h)	6
Diode, single element	670-980	< 40	0.15	-	> 1 GHz	ps to ms	< 1 > 1000 (h)	9 Clementine, Mars Obs.
Diode Bar Array, (stack)	670-980	< 30	200w, 2000	0.1	< 1.5 kHz	ps to ms	< 1 2 (h)	8
Diode, MOPA	670-980	< 20	3	-	1 GHz	ps to ms	< 2 -	5.6
Diode	1200-1580	< 30	0.2	-	> 1 GHz	ps to ms	< 1 > 1000 (h)	6.7
Lead Salt diode	2800-3000	< 10	0.003	-	-	-	< 1 (< 1 (h)	6
Alexandrite	720-800	< 1	40	100	1-20	0.05	> 50 > 1 (h)	0
Ti: Sapphire	680-1100	< 1	0.5	0.3	1-20	0.01	> 50 > 1 (h)	6
Na: Glass	1050	< 2	100	22	0.008	ns to ms	> 50 > 1000 (h)	6
Na: YAG, Na: ...	1200-1350	< 2	20	1 k	1-5 kHz	ns to ms	> 100 2000 (sh)	6
Na: YAG	1064	10	10	0.01	200 kHz	2-90 ns	< 5 > 1000 (h)	9 Clementine, Mars Obs.
diode-pnd-Pumped	532	5	5	0.005	20 MHz [1]	2-90 ns	< 5 > 1000 (h)	8
Na: YAG	1064	10	10	0.01	200 kHz	2-90 ns	< 5 > 1000 (h)	9 Clementine, Mars Obs.
Na: YAG	1064	< 1 k	1	1	1 kHz	100 ns	< 50 > 2 (h)	6
diode pumped	1064	1	45	1.5	30	10 ns	100 1000 (sh)	6
Na: YAG	1064	10	2	0.1	50 kHz	20-200 ns	< 5 > 1000 (h)	6
Ti:Ho:Crystal	2000	1	80	4	20	50 ns	100 100 (sh)	6
Flashlamp	694	< 1	100	> 100	30	ns-ms	> 100 > 1000 (sh)	6
Ruby	694	< 1	100	> 100	30	ns-ms	> 100 > 1000 (sh)	6
OPO	700-3000	< 2	10	0.5	2 kHz	> 0.1 ms	> 50 > 2 (h)	6
Color center	1500-2500	< 1	0.5	-	-	-	> 20 < 0.1 (h)	6
Er: Crystal	2940	< 2	40	1	10	250 ms	> 50 < 0.1 (h)	6

[1] PRF is lower in Q-switch mode operation. It can be increased to about 20 MHz when cavity-dumped.

lasers are limited to ground based low data rate uplink transmitter.

Single element laser diodes operating in the near IR and IR range, diode bar arrays, and MOPA laser diodes and their parameters are listed in Table V. Semiconductor diode lasers operating in the 670-980 nm wavelength range match most of the required characteristics for optical communications. The average power of a diode laser with good beam quality, however, is limited to about 0.15 W. Such lasers are ideal for near earth applications where modest optical output power is sufficient to accomplish the communication link. Master-oscillator power amplifier (MOPA) diode lasers, developed recently, can provide as much as 3 W of continuous wave (CW) power. MOPAs are less developed (NASA readiness level 5 or 6), more massive than the diode, and their reliability is uncertain at this time. Diodes in the 1.2 to 1.58 μm wavelength are well developed due to extensive developmental work in the fiber optics field. However, use of longer wavelength diodes in free space communications reduces possible data rates significantly.

Several solid state lasers are listed in Table V. Most of these lasers are heavy (> 20 kg), have low modulated efficiency (< 2 percent), and their operating life time is less than one year. Such solid state lasers are not attractive for use in space. Only diode pumped Nd:YAG and diode pumped Tm/Ho:Crystal lasers provide reasonable match with the requirements of an optical communications system.

The diode pumped Nd:YAG at 1.06 μm , which is the most developed and has been used in space, or its frequency doubled operation at 0.53 μm , and diode pumped Tm/Ho:Crystal laser in the 1.89 to 2.16 μm wavelength range have high modulated efficiency (up to 20 percent undoubled) and long operating life time ($> 10^6$ hours). These laser systems can weigh several kilograms, but are much less than other solid state lasers. While the diode pumped solid state lasers are heavier than the laser diodes, they provide significantly higher optical output power at good modulated power efficiency. These lasers are suitable for deep space spacecraft where high output power is necessary to accomplish the communication link. Nd:YAG lasers can be Q-switched at a maximum pulse repetition frequency (PRF) of about 200 KHz or cavity-dumped with a bandwidth of about 20 MHz. These limits on the PRF restricts the use of such lasers to data rates less than 20 Mb/s.

B. LASER SELECTION IMPACT ON WAVELENGTH CHOICE

The impact of laser technology on laser communications terminals in space and on the ground is described below.

1. Laser for Spacecraft Transmitter

Semiconductor diode lasers operating between 0.67 to 0.98 μm are well suited for optical communications when

the power requirements of the link are modest. These lasers are ideal for near earth applications. Diode lasers can be modulated at data rates in the Gb/s range. A wavelength about 850 nm is especially well-suited since the Si APDs quantum efficiency peaks at this wavelength. The laser diodes in the 1200 to 1580 nm range and related technology including modulators and detectors are well developed due to years of intensive efforts in the fiber optics field. If longer operating wavelength is chosen for this reason, InGaAs or Ge APD can be used with diodes in the longer wavelength range. The system performance, however, is significantly lower when using longer wavelength. For example, a 0.5 Gb/s LEO to GEO link is possible using 850 nm laser diode and a Si APD detector with a 0.1 m aperture and earth in the background [6]. If a diode laser at 1500 nm wavelength is used with the InGaAs APD under similar link design values, the possible data rate decreases by an order of magnitude to about 50 Mb/s.

Performance of diode pumped Nd:YAG lasers in optical communication systems has been studied in great detail, and prototype designs and engineering models have been demonstrated [66-67]. This laser system is very attractive as it provides high transmitter power with good beam quality, low mass (~ 2 kg), and excellent reliability. It can be operated at 1.06 μm , or its frequency doubled version at 0.53 μm . Modulation technology, however, limits possible data rates to less than 20 Mb/s. Diode pumped Tm/Ho:Crystal laser system, though less developed (NASA readiness level 6), has the potential to provide similar modulation technology limited performance at wavelengths about 2 μm .

2. Laser for Ground Transmitter

Reliability, mass, power consumption, and thermal management requirements are less of an issue for ground transmitter laser. Additionally, the uplink data rate traditionally provided by the DSN is low (~ 1 Kb/s). This opens up the types of lasers that can be chosen, and consequently the range of wavelengths that can be used for uplink. Flash lamp or diode pumped solid state lasers can be used for deep space missions operating at 0.53, 1.06, or 2 μm wavelength. Other laser systems, when short operating life time is not an issue, copper vapor, iodine, or the carbon dioxide lasers can be used at 0.51, 1.3, 10.6 μm wavelength, respectively.

Diode lasers operating between 0.67 to 0.98 μm wavelengths are ideal for range limited applications, i.e., near-earth optical communications for ground-to-satellite links. Such links can be accomplished at high data rates and can be suitable for commercial use.

VIII. OTHER RELEVANT ISSUES

Other relevant issues that may have an impact on the selection of operating wavelength for laser communication system include availability and characteristics of spectral filters and the ability to meet the necessary pointing

Table VI Spectral optical filters

Filter	Bandwidth nm	Transmission	FOV rad	Clear aperture cm	Tunability	Stability	Wavelength coverage
FADOF [1]	0.001	0.6	0.3 - 3	Large	Low	High	Specific Wavelengths
Interference	≥ 0.2	0.7	0.1	15	High	Low	UV to IR
Fabry-Perot	0.005	0.5	0.02	5	High	High	UV to IR
Birefringent	0.05	0.25	0.02	7	High	High	UV to near IR

1) Faraday Anomalous dispersion optical filter

requirements to acquire and track the communication terminal at the other end of the link.

A. SPECTRAL FILTERS

Optical communication systems are required to function under diverse, sometimes hostile, channel noise conditions. Spectral optical filters (SOF) and their characteristics necessary to achieve high propagation FOM have been studied in detail [68-72]. It is shown that the impact of SOF selection under most conditions is minimal on the choice of laser communication wavelength, except under special conditions when use of an atomic line filter (ALF) like the Faraday anomalous dispersion filter (FADOF) is essential to accomplish the link.

Table VI shows a list of possible SOFS for laser communications. It shows bandwidth, efficiency, clear aperture, tunability, stability, and the range of wavelengths for which the spectral filter can be used. Restrictions on filter parameters including clear aperture size, tunability, and stability result from considerations on manufacturability, and the suitability of available materials.

ALF provides the best match with the desired requirements for laser communications [69-70]. ALF has high transmittance, extremely narrow passband defined by atomic line width, wide FOV, and good stability (see Table VI). However, the ALF in its present state of development (NASA readiness level 2) drastically restricts operation of laser communication system to a few specific wavelengths, mostly in the visible and the near IR. Additionally, the extremely narrow ALF bandwidth and its center wavelength may not optimally match the chosen laser wavelength. ALF can possibly be used to advantage in ground based receiver systems under high background noise, e.g., in day-time conditions when lasers with matching center wavelength can be found.

Conventional narrowband SOFS can be built for any given wavelength, but have larger bandwidth, and restricted FOV compared to the ALF (see Table VI) [71-72].

Interference, Fabry-Perot, and other conventional filters can be engineered for any specified wavelength. Consequently, the impact of spectral filters on the choice of operating wavelength for the laser communication system,

when conventional SOFS will do, is minimal. If an ALF is essential to accomplish the link, the set of available wavelengths is extremely limited at this time.

B. POINTING REQUIREMENTS

Pointing requirements become increasingly stringent for shorter wavelengths as the beamwidth decreases. It is estimated that the optimum beamwidth is about a factor of 4 larger than the beam pointing error [73]. Fig. 6 shows normalized pointing requirements with respect to 400 nm wavelength obtained from beamwidth considerations alone. It was estimated that pointing with $0.1 \mu\text{rad}$ accuracy is needed for a strenuous Pluto mission using 0.6 m transmitter and 532 nm operating wavelength, and that such an accuracy can be achieved with some technology development [7]. Pointing requirements for many deep space and near earth missions are much less stringent ($\sim 1 \mu\text{rad}$) and can be accomplished with little impact on the choice of wavelength for laser communications.

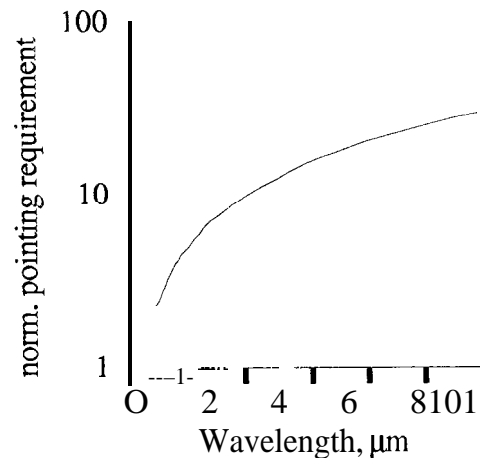


Fig. 6 Normalized pointing requirements for diffraction limited beams as a function of wavelength.

Table VII. Summary of recommended downlink wavelengths for selected missions

Mission	Realizable data rates [1]				
	~100 Kb/s	~1 Mb/s	~10 Mb/s	~100 Mb/s	~1 Gb/s
Near-Earth [2]					850 nm
Mars			532/1064 nm [3]		
Saturn	1064 nm	532 nm			
Pluto	1064 nm	532 nm			

[1] Sub-columns show order of magnitude of realizable data rates. Data rates less than the indicated order of magnitude are possible using the same recommended wavelength, [2] Include LEO, Intersatellite, GEO, and Lunar missions, [3] Limited by modulability of solid state lasers.

IX. CONCLUSION

A study of contributing factors including propagation, channel noise and available technology has been made to shed light on the selection of wavelengths for free space laser communications. Table VII provides a summary of recommended downlink wavelengths for selected missions. The data rates shown in the table should be considered as order of magnitude estimates for realizable missions. Actual telemetry capacity for specific missions strongly depends on the mass, power, and size allocations for the spacecraft communications terminal, the size of the receiver, and the operating characteristics of the communications channel.

Diode lasers operating at 850 nm are best suited for near earth applications. Near earth missions include LEO, GEO, Intersatellite, and Lunar missions. Laser diodes in this range (670-980 nm) of wavelengths are well developed, are matched well with the detector technology, are compact, light in weight, low in power consumption, good in beam quality, and provide necessary signal power to accomplish telemetry links in the gigabit range. Additionally, the transmission characteristics of the turbid and turbulent atmosphere can be managed adequately for the probable near earth missions.

For most deep space missions high pulse energies are needed to produce a viable communication link, eliminating diode lasers from consideration at the present time. Use of doubled Nd:YAG laser at 532 nm is well suited to provide high data rate (~10 Mb/s) downlink, even though the atmospheric conditions are harsh compared to longer wavelengths. The propagation FOM as defined earlier to quantify impact of propagation and background noise is found to be excellent for nighttime operation at 532 nm wavelength (-60 dB better when compared to 10.6 μ m wavelength). For the worst case background optical noise (SEP angles less than 10°) the propagation FOM for 532 nm is of the same order as all other wavelengths less than or equal to 4 μ m, and is about 10 dB better when compared to 10.6 μ m wavelength. Considerations of technology (e.g., simpler design of undoubled Nd:YAG) or of optical navigation may impel the designer to use 1064 nm wavelength, but with significantly reduced telemetry.

Diode lasers operating at 850 nm are recommended for range-limited uplink (ground-to-satellite) applications at

high telemetry rates (up to 1 Gb/s) when enough power is available to provide necessary fade margin (7.1 dB). For the uplink, when the transmitter is on ground and the atmosphere is close to the transmitter, and the command uplink data rate is low, a wavelength between 1000 to 2000 nm is recommended to effectively deal with scintillation and beam wander. Assuming no adaptive optics, Table I in Sec. III.B.2 shows that a 4 dB fade margin is necessary to deal with the scintillation for 99 percent operation of the command uplink at 2000 nm wavelength.

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